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# Quality of dredged material in the river Seine basin (France). II. Micropollutants

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**Abstract**

Dredging rivers is needed to ensure safe navigable waters, rivers and waterways. To anticipate the management of dredged materials in the case of the river Seine basin, the quality of the sediments in the river is checked every 3 years before dredging operations. The river Seine Basin is heavily submitted to pollution pressure from nearby industrial activities and urban expansion of Paris and its region. Here, the micropollutant content of the sediment sampled in 1996, 1999 and 2000 before dredging is discussed compared to regulatory standards. The results indicate that most of the sediment samples from the river Seine basin are lightly to moderately contaminated with organic and inorganic micropollutants (heavy metals, PAH, PCB), which makes the management after dredging easier. This pollution is strongly correlated with the organic matter content and to the fine fraction ($<50$ μm) of the sediment. These results can lead to other management options than the ones already used in the river Seine basin: (1) dumping of lightly to moderately polluted sediments in quarries; and (2) physical treatment (sieving, hydrocycloning) of contaminated sediments issued from 'hot spots'.
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*Keywords:* Dredged material; Sediments; Quality; River Seine basin; Heavy metals; PAH

## 1. Introduction

The increasing urban environmental pollution and human impact leads to water quality deterioration. With the release of polluted water into the receiving water bodies, contaminants are absorbed onto suspended particles and subsequently accumulated in the underlying sediment (Hauge et al., 1998; Lau and Chu, 1999). Hence, dredging contaminated sediments means removing the pollution which is contained in the sediment.

Dredging techniques vary depending on the volume, texture, water content and grain size of the sediments to be removed. The method that causes the least environmental impact on the water

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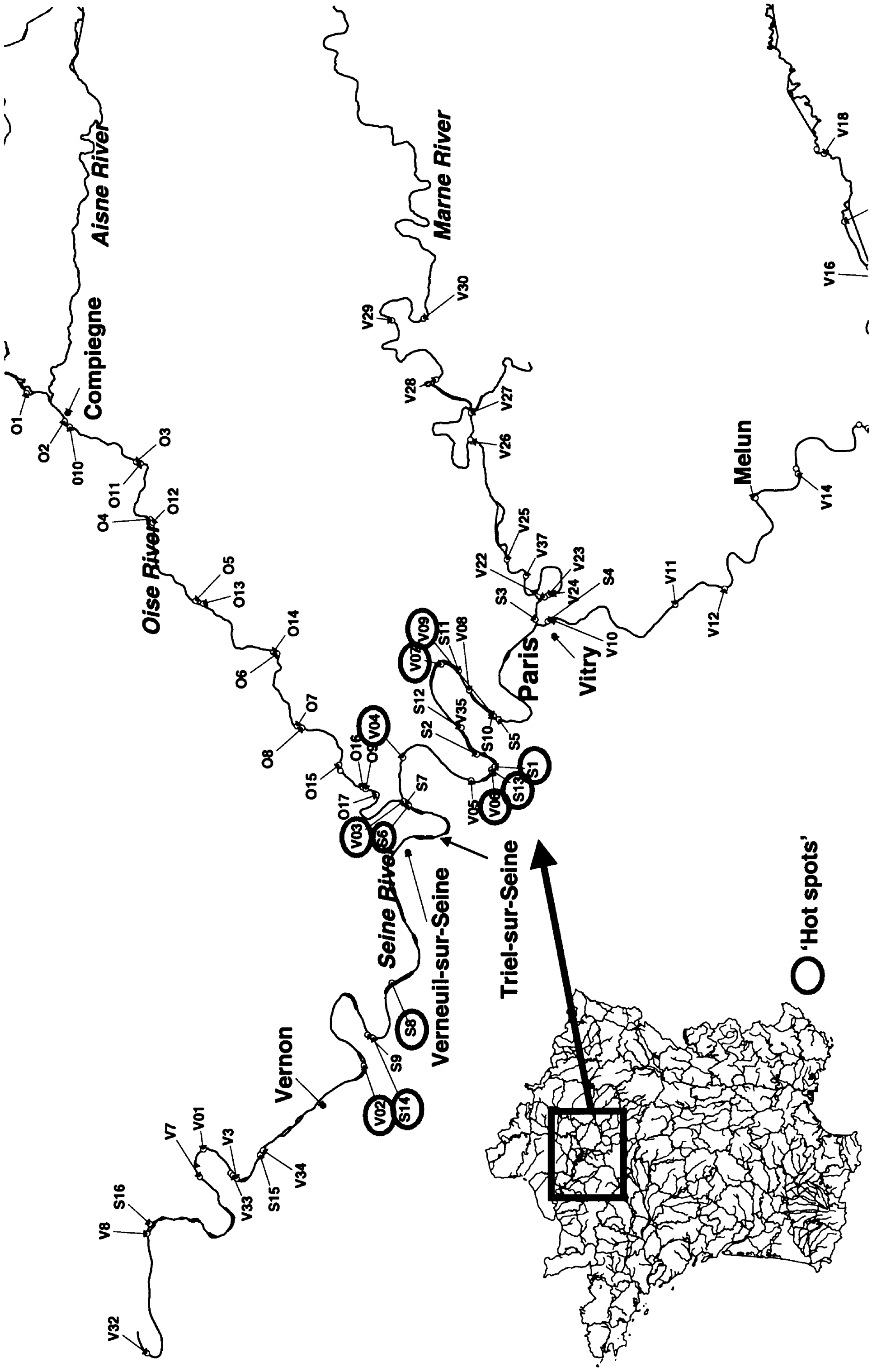


Fig. 1. Part of the Seine basin concerned in this study and site codes corresponding to the sediment samples collected during 1996, 1999 and 2000 campaigns: 'Hot spots' i.e. sites of significant sediment contamination appear within circles.

Table 1
List of micropollutants determined in the sediment (S) sampled in 1996, 1999 and 2000, in the leachates (L) and in the pore water (P), methods used to analyse each parameter and detection limits (dl) for the different methods

| Analysis | Method | Analysis | Sample | dl (S) (μg g$^{-1}$) | dl (L) (μg g$^{-1}$) | dl (P) (μg l$^{-1}$) |
|---|---|---|---|---|---|---|
| Total hydrocarbons | X 31-410 ISO TR 11046 | IR | S, L, P | 20 | 1 | 50 |
| Total PAH (16 EPA species) | NF T 90-115 | HPLC | S, L, P | 0.01 | 0.01[a] | 0.01 |
| Total aliphatic hydrocarbons | | GC/FID | S, L, P | 2 | 20[a] | 20 |
| Toluene | NF ISO 11423-1 | GC/FID | S | 0.1 | nd | nd |
| Pesticides | NF EN ISO 6468 T90-120 | GC/MS | S | 0.15 | nd | nd |
| Total PCB (6) | NF EN ISO 6468 T90-120 | GC/ECD | S | 0.005 | nd | nd |
| As | NF EN ISO 11885 | ICP/AES | S, L, P | 5 | 0.05 | 5 |
| Cd | NF EN ISO 11885 | ICP/AES | S, L, P | 0.8 | 0.02 | 2 |
| Cu, Cr, Ni, Pb, Zn | NF EN ISO 11885 | ICP/AES | S, L, P | 5 | 0.1 | 10 |
| Al | NF EN ISO 11885 | ICP/AES | S, L, P | 5 | 1 | 10 |
| Fe, Mn | NF EN ISO 11885 | ICP/AES | S, L, P | 5 | 0.1 | 10 |
| Hg | XP T 90-113-2 | Atomic fluorescence | S, L, P | 0.05 | 0.005 | 0.5 |
| Phenolic compounds | Acidic extraction | GC/MS | S, L | 2 | nd | nd |

[a] μg/l.

quality, during dredging operations, is the hydraulic method. However, mechanical dredging yields materials containing high solid levels: this is an important criteria given for better management of dredged material (DM), i.e. avoiding large water volumes management (Hauge et al., 1998).

Once dredged, DM can be treated, valorised, or disposed. Before any management decision, it is necessary to characterise the DM chemically, physically and mechanically (Boutouil et al., 1997). However, the economic, political context and management issues, such as the lack of disposal sites, can interfere with the decision provided by the characterisation of DM. In the specific case of the river Seine basin, mechanical dredging from a boat was chosen to remove approximately 150 000 m$^3$ of sediment per year from the Seine basin. Dredging in the Seine basin is mainly 'maintenance dredging' for navigation. DM is then dumped into wet disposal sites, i.e. disused quarries, downstream Paris. From 1992 to 1998, the site of Triel and from 1999 to 2001, the site of Rouillard have been filled with the DM extracted from the river Oise downstream Compiègne and from the river Seine downstream Vitry (Fig. 1). According to an estimate in the 1980s by the US Army Corps of Engineers (Combs et al., 1982) and in a recent study in the Netherlands (Cuypers et al., 1998), approximately one third of all dredged materials are contaminated by municipal sewage, industrial discharges and agricultural runoff.

In a previous paper (Carpentier et al., 2002), we characterised the physico-chemical properties and major contamination patterns of the sediments sampled from the river Seine basin before dredging. This work revealed the wide variety of the sediment quality, particularly the carbon content and the grain size, along the river Seine basin. The analysis of porewaters revealed high concentrations in ammonium that might lead to a management concern: in fact, the dumping of such sediment after dredging might induce an increase of ammonium concentrations in the receiving waters at the disposal sites (Carpentier et al., 2001). After correlation analysis and geographic distribution study, the impact of the great Parisian region (including Paris itself and close counties) was not clearly observed. This impact was only observed when the location of the sediment sample was far enough, i.e. approximately 100 km from the urban and/or industrial sources. For example, samples V30 or V18 on Marne and Seine river, respectively, upstream Paris showed very different organic matter contents compared to S1 or S6 on Seine river downstream Paris. In order to improve our knowledge on the quality of river Seine basin

Table 2
Metal content ($\mu g\ g^{-1}$) in the sediment collected in 1996, 1999 and 2000

| Code | Y[a] | As | Cd | Cr | Cu | Hg | Ni | Pb | Zn | Al | Fe | Mn | Code | Y[a] | As | Cd | Cr | Cu | Hg | Ni | Pb | Zn | Al | Fe | Mn |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| V01 | 1996 | | <0.8 | <10 | 12 | 0.76 | <5 | 32 | 70 | | | | S6 | 1999 | <5 | 1.8 | | 62 | 0.64 | 10 | 103 | 220 | 2600 | 3300 | 38 |
| V02 | 1996 | | <0.8 | <10 | 28 | 15.5 | <5 | 50 | 98 | | | | S7 | 1999 | <5 | 3 | | 83 | 0.92 | 19 | 83 | 293 | 3800 | 8200 | 50 |
| V03 | 1996 | 6.93 | <0.8 | 46 | 172 | 1.61 | 22 | 194 | 535 | | | | S8 | 1999 | <5 | 3 | | 90 | 0.64 | 16 | 69 | 250 | 1800 | 7200 | 43 |
| V04 | 1996 | 3.33 | <0.8 | 24 | 102 | 6.31 | <5 | 132 | 240 | | | | S9 | 1999 | <5 | 1.5 | | 54 | 0.65 | 20 | 70 | 225 | 2200 | 15 100 | 39 |
| V05 | 1996 | | <0.8 | 24 | 80 | 2.78 | <5 | 174 | 290 | | | | V1 | 1999 | <5 | <0.8 | 44 | 91 | 0.8 | 17 | 42 | 278 | | | |
| V06 | 1996 | | <0.8 | 22 | 92 | 5.55 | <5 | 158 | 246 | | | | V2 | 1999 | 6 | <0.8 | 48 | 96 | 0.8 | 18 | 9 | 295 | | | |
| V07 | 1996 | 5.69 | 6 | 46 | 122 | 2.5 | 20 | 278 | 563 | | | | V3 | 1999 | <5 | <0.8 | 13 | <5 | <0.05 | <5 | <5 | 58 | | | |
| V08 | 1996 | 4.08 | <0.8 | 20 | 70 | 2.35 | <5 | 152 | 236 | | | | V4 | 1999 | <5 | <0.8 | 25 | 29 | <0.05 | <5 | 12 | 88 | | | |
| V09 | 1996 | | <0.8 | <10 | 64 | 5.9 | <5 | 136 | 283 | | | | V5 | 1999 | <5 | <0.8 | 10 | <5 | 0.1 | <5 | 15 | 46 | | | |
| V10 | 1996 | | <0.8 | 20 | 68 | <0.05 | <5 | 74 | 168 | | | | V6 | 1999 | <5 | <0.8 | 16 | 26 | 0.192 | <5 | 43 | 100 | | | |
| V11 | 1996 | | <0.8 | <10 | 42 | <0.05 | <5 | 82 | 118 | | | | V7 | 1999 | <5 | <0.8 | 13 | 8 | 0.109 | <5 | 12 | 43 | | | |
| V12 | 1996 | | <0.8 | <10 | 16 | <0.05 | <5 | 48 | 52 | | | | V8 | 1999 | 6 | <0.8 | 78 | 73 | 0.414 | 24 | 80 | 300 | | | |
| V13 | 1996 | | <0.8 | <10 | 22 | <0.05 | <5 | 118 | 94 | | | | O1 | 1999 | <5 | <0.8 | | 9 | 0.29 | 14 | 42 | 81 | 6600 | 17 000 | 15 |
| V14 | 1996 | | <0.8 | <10 | 10 | 0.37 | <5 | 36 | 32 | | | | O2 | 1999 | <5 | <0.8 | | <5 | 0.09 | 6 | 24 | 39 | 6100 | 9400 | 9 |
| V15 | 1996 | | <0.8 | <10 | 14 | 0.27 | <5 | 44 | 26 | | | | O3 | 1999 | <5 | <0.8 | | 24 | 0.3 | 20 | 33 | 141 | 5900 | 14 500 | 25 |
| V16 | 1996 | | <0.8 | <10 | 60 | 1.28 | <5 | <5 | 76 | | | | O4 | 1999 | <5 | <0.8 | | 16 | 0.3 | 17 | 28 | 99 | 5100 | 12 300 | 18 |
| V17 | 1996 | | <0.8 | <10 | 16 | 0.36 | <5 | <5 | 30 | | | | O5 | 1999 | <5 | <0.8 | | 27 | 0.39 | 22 | 51 | 183 | 3100 | 2300 | 32 |
| V18 | 1996 | | <0.8 | <10 | 44 | <0.05 | <5 | <5 | 54 | | | | O6 | 1999 | <5 | <0.8 | | 14 | 0.3 | 8 | 32 | 86 | 6800 | 8600 | 16 |
| V19 | 1996 | | <0.8 | <10 | 12 | <0.05 | <5 | <5 | 36 | | | | O7 | 1999 | <5 | <0.8 | | 26 | 0.37 | 20 | 50 | 173 | 6900 | 18 300 | 30 |
| V20 | 1996 | | <0.8 | <10 | 14 | <0.05 | <5 | 56 | 80 | | | | O8 | 1999 | <5 | <0.8 | | 32 | 0.45 | 20 | 58 | 185 | 12 900 | 11 200 | 32 |
| V21 | 1996 | | <0.8 | <10 | 14 | <0.05 | <5 | 214 | 260 | | | | O9 | 1999 | <5 | <0.8 | | 28 | 0.44 | 21 | 53 | 103 | 5300 | 23 000 | 19 |
| V22 | 1996 | | <0.8 | 28 | 68 | <0.05 | <5 | 86 | 238 | | | | S10 | 2000 | 11 | 0.91 | 36 | 114 | 0.53 | 20 | 80 | 247 | 28 661 | 29 177 | 469 |
| V23 | 1996 | 3.35 | <0.8 | <10 | 28 | 0.31 | <5 | 38 | 82 | | | | S11 | 2000 | 6 | <0.8 | 11 | 23 | 0.18 | 9 | 44 | 116 | 6652 | 6643 | 243 |
| V24 | 1996 | | <0.8 | 20 | 50 | 0.28 | <5 | 72 | 144 | | | | S12 | 2000 | 13 | 1.33 | 48 | 131 | 0.56 | 28 | 107 | 355 | 32 778 | 34 240 | 495 |
| V25 | 1996 | | <0.8 | 24 | 48 | <0.05 | <5 | 70 | 132 | | | | S13 | 2000 | <5 | <0.8 | 11 | 27 | 0.25 | <5 | 64 | 87 | 3119 | 4676 | 199 |
| V26 | 1996 | | <0.8 | <10 | 20 | <0.05 | <5 | <5 | 78 | | | | S14 | 2000 | 13 | 2.06 | 73 | 136 | 0.76 | 30 | 102 | 450 | 36 148 | 36 960 | 509 |
| V27 | 1996 | | <0.8 | <10 | 18 | <0.05 | <5 | 42 | 60 | | | | S15 | 2000 | 10 | 1.65 | 63 | 127 | 0.64 | 25 | 88 | 400 | 34 464 | 33 711 | 456 |
| V28 | 1996 | | <0.8 | 20 | 38 | <0.05 | <5 | 58 | 118 | | | | S16 | 2000 | 12 | 1.66 | 63 | 120 | 0.65 | 26 | 83 | 380 | 30276 | 36 787 | 484 |
| V29 | 1996 | | <0.8 | 20 | 26 | <0.05 | <5 | 32 | 88 | | | | O10 | 2000 | 11 | <0.8 | 40 | 28 | 0.15 | 23 | 24 | 144 | 24 488 | 39 859 | 343 |
| V30 | 1996 | | <0.8 | <10 | 30 | <0.05 | <5 | 42 | 90 | | | | O11 | 2000 | 6 | <0.8 | 34 | 28 | 0.15 | 17 | 39 | 136 | 15 886 | 21 756 | 356 |
| V31 | 1996 | | <0.8 | 24 | 56 | <0.05 | <5 | 32 | 132 | | | | O12 | 2000 | 10 | <0.8 | 41 | 32 | 0.17 | 20 | 30 | 179 | 25 105 | 32 261 | 379 |
| S1 | 1999 | <5 | 3 | | 94 | 24 | 24 | 144 | 286 | 1800 | 9700 | 49 | O13 | 2000 | 9 | <0.8 | 35 | 31 | 0.23 | 16 | 33 | 191 | 21 337 | 31 955 | 419 |
| S2 | 1999 | <5 | <0.8 | | 56 | 0.49 | 16 | 71 | 188 | 3000 | 5600 | 33 | O14 | 2000 | 12 | 0.92 | 49 | 39 | 0.26 | 24 | 38 | 225 | 32 588 | 38 650 | 481 |
| S3 | 1999 | <5 | <0.8 | | 30 | 0.23 | 14 | 62 | 122 | 5900 | 5300 | 22 | O15 | 2000 | 7 | <0.8 | 26 | 23 | 0.21 | 11 | 28 | 125 | 1562 | 15 496 | 358 |
| S4 | 1999 | <5 | <0.8 | | 85 | 0.56 | 15 | 198 | 414 | 5000 | 5600 | 70 | O16 | 2000 | 11 | <0.8 | 40 | 42 | 0.28 | 19 | 44 | 220 | 23 764 | 35 368 | 406 |
| S5 | 1999 | <5 | 1.3 | | 60 | 0.51 | 21 | 73 | 210 | 2600 | 10 900 | 37 | O17 | 2000 | 7 | <0.8 | 30 | 32 | 0.28 | 14 | 35 | 171 | 4017 | 20 921 | 391 |

See Fig. 1 for sampling site location.
[a] Year of collection.

Table 3
Metal content ($\mu g\ g^{-1}$) of the sediments collected before dredging in the Seine Basin in 1996, 1999 and 2000

| Site | | As | Cd | Cr | Cu | Hg | Ni | Pb | Zn | Al | Fe | Mn | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Seine River, 1996–2000 | $n$ | 41 | 42 | 32 | 50 | 50 | 50 | 50 | 50 | 33 | 33 | 33 | This study |
| (sediment) | $d_{10}$ | <5 | <0.8 | 10.1 | 0 | 0.15 | 3.6 | 23.1 | 79.9 | 2280 | 5360 | 18.2 | |
| | $d_{50}$ | <5 | 0.8 | 32 | 31.5 | 0.45 | 17 | 52 | 189 | 6100 | 15 100 | 50 | |
| | $d_{90}$ | 11 | 2.0 | 61.6 | 120.2 | 3.06 | 24 | 152.6 | 382 | 32 126 | 36 503 | 479 | |
| | Min | <5 | <0.8 | 4 | <5 | <0.05 | <5 | <5 | 39 | 1562 | 2300 | 9 | |
| | Max | 13 | 6 | 78 | 172 | 24 | 30 | 278 | 563 | 36 148 | 39 859 | 509 | |
| | Mean | 3.8 | 1.1 | 32.5 | 49.3 | 1.65 | 14.7 | 72.0 | 210 | 12 371 | 18 362 | 199 | |
| | SD | 4.9 | 1.1 | 20.0 | 44.4 | 4.1 | 8.4 | 57.2 | 123 | 11 780 | 12 291 | 195 | |
| | CV | 129 | 107 | 62 | 90 | 247 | 58 | 79 | 59 | 95 | 67 | 98 | |
| Seine River, 1996–1998 | Min | | 0.8 | 43 | | | | 82 | 192 | | 16 600 | | Meybeck et al., 1998 |
| (TSS) | Max | | 7.9 | 380 | | | | 300 | 825 | | 25 300 | | |
| | Annual mean | | 2.7 | | 88 | 0.9 | | 109 | 401 | 52 700 | | | |
| North of France River | Mean | | 2.8 | 133 | 220 | | 42 | 360 | 1180 | | | | Ruban et al., 1998 |
| Detroit River, USA | Mean | | 7.2 | 129 | 85.1 | | 71.3 | 176.0 | 792 | | | | Besser et al., 1996 |
| Elbe River, Germany (TSS) | Mean | | 11.5 | | 150 | 6 | | | 1500 | | | | Netzband et al., 1998 |
| Danube River, Hungary | Mean | | 0.8 | 70.7 | 42 | | 36 | 47.8 | 159 | | | | Gruiz et al., 1998 |
| Rio de Janeiro River, Brazil | Mean | 3.4 | | | 28.6 | | 13.6 | 44.2 | 110 | | | | Almeida et al., 2001 |
| Canal, Belgium | Mean | | 12.9 | 267 | 128 | | | 721 | 3200 | 14 580 | 29 000 | 2480 | Cauwenberg et al., 1998 |

Number of samples ($n$), median ($d_{50}$), first and last decile ($d_{10}$, $d_{90}$), minimum and maximum (min, max), standard deviation (SD) and coefficient of variation in % (CV) of the data given in Table 2.

sediments, we also analysed the micropollutants in the sediments. Here, we are not only interested in the sediment quality itself, but we are also concerned about the quality of the DM that it becomes, after extraction from the river bed, and its fate once moved to another receiving environment. For that reason, we also analysed micropollutants in porewaters of the sediments and leachates obtained with the same sediment samples. The study of leachates is, in the case of disposal, one of the techniques recommended by the French standard NF XP X 31-210 for assessing the impact of materials on their close environment, after dumping. The study of porewaters was also performed in order to assess the potential release of pollutants that might occur during the management of DM. The aim of this work is to translate these sediment and pore quality data into dredging and treatment strategies for the river Seine basin.

## 2. Material and methods

### 2.1. Sediment collection

The sampling procedure has been fully described previously. Briefly, samples were collected from the bottom of the rivers Seine, Oise and Marne by handcore sampling (20–50 cm depth depending on the DM quality) (Fig. 1). Samples were collected in May and June 1996, April 1999 and May 2000 in representative areas determined by the Navigation Services of the Seine basin (SNS), according to the dredging needs for the following year, resulting from bathymetric survey of the river. Once cored, sediment samples were transferred into fully filled and closed glass containers (1 l) and were kept in a store room (4 °C) for 48 h maximum before homogenisation and analysis.

### 2.2. Methods

Different parameters were analysed both on the sediment (Table 1) and in the leachates obtained with the same sediment samples. Leachates were resulting from mixing 200 g of bulk sediment for 24 h with 2 l of distilled water, according to the French AFNOR standard XP X31-210. Parameters were also measured on pore waters. The method to extract pore waters is described in a previous paper (Carpentier et al., 2002). Most parameters were measured following the French standard procedures i.e. AFNOR (Table 1). All samples were analysed by laboratories certified by the French Ministry of the Environment, i.e. certified by the COFRAC (Comité Français d'Accréditation). For international quality control, the COFRAC calibration certificates co-operates with other European calibration services (the European co-operation for Accreditation, EA). The harmonisation of the accreditation criteria and procedures are orientated towards the European standards for calibration and testing laboratories and their assessment and accreditation (EN ISO/IEC 17025 and EN 45 000 series). The detection limits for inorganic and organic micropollutant content of sediment samples were chosen in order to be significantly below regulatory standards (Table 1).

Table 4
Alert values (A) and Intervention values (I) for soil remediation ($\mu g\ g^{-1}$)

| Pollutant | A. Alert value | I. Intervention value |
|---|---|---|
| As | 29 | 55 |
| Cd | 0.8 | 12 |
| Cr | 100 | 380 |
| Cu | 36 | 190 |
| Hg | 0.3 | 10 |
| Ni | 35 | 210 |
| Pb | 85 | 530 |
| Zn | 140 | 720 |
| Benzene | 0.05 | 2 |
| Toluene | 0.05 | 130 |
| $PCB_{tot}$[a] | 0.02 | 1 |
| $PAH_{tot}$[b] | 1 | 40 |
| DDT+DDD+DDE | 0.0025 | 4 |
| Alkanes | 50 | 5000 |
| $Phtalates_{tot}$ | 0.1 | 60 |
| HCH | – | 2 |

Dutch circular, 04/02/2000, Ministry of Housing, Spatial Planning and Environment, Holland.

[a] $PCB_{tot}$ = sum of PCB 28, 52, 101, 118, 153, 180.

[b] $HAP_{tot}$ = sum of 10 PAH [Anthracene, Fluoranthene, Benzo(*k*)fluoranthene, Benzo(*ghi*)perylene, Indeno(123-*cd*)pyrene, Benzo(*a*)anthracene, Benzo(*a*)fluoranthene, Chrysene, Naphtalene, Phenanthrene].

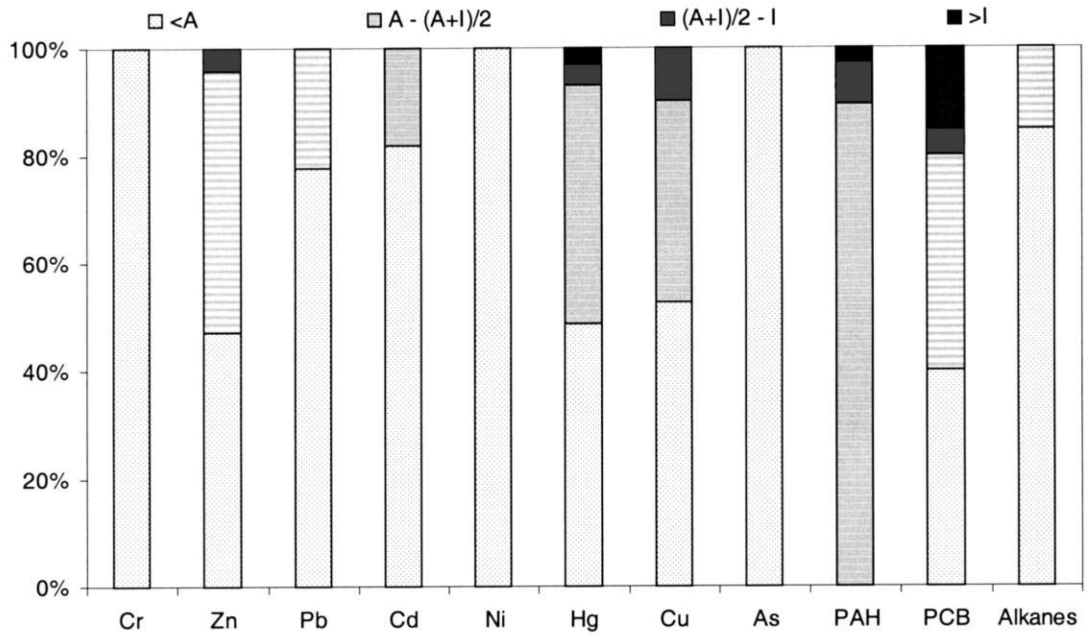


Fig. 2. Statistical distribution of the number of sediment samples presenting a contamination in heavy metals or organic micropollutants below (<A) the Alert value of the Dutch decree on the quality of sediments, above (>I) the Intervention value of this decree, or within these two values.

## 3. Results and discussion

### 3.1. Sediment quality

#### 3.1.1. Heavy metals

The average metal content of the sediment collected in various dredged areas of the river Seine basin (Table 2 and Table 3) is generally slightly lower than the average values found in the total suspended solids (TSS) from the river Seine basin (Meybeck et al., 1998). In fact, in the case of Zn, levels vary from 190 to 700 $\mu g\ g^{-1}$ in the TSS, whereas in the sediment analysed in the present study, concentrations vary from 40 to 560 $\mu g\ g^{-1}$. The same difference is observed for Cd, Cu, Pb. This slight difference can be explained by the nature of the sediment itself. As we found out previously (Carpentier et al., 2002), grain size of sediments from the river Seine basin, and particularly the percentage of particles below 50 $\mu m$ is on average 20%. In the study concerning TSS, this percentage was ranging from 40 to 45%. This may explain the higher heavy metal content in TSS samples, compared to sediment samples, because heavy metals are preferably adsorbed on fine particles (Evans et al., 1990; Warren and Zimmermann, 1994; Perrin and Zimmer, 1995). However, the difference observed between sediments and TSS from the river Seine basin remains small compared to the difference of heavy metals content between sediments sampled at different locations of the Seine basin.

Concentrations of metallic pollutants found in the sediment sampled in the Seine basin are low (210 $\mu g\ g^{-1}$ on average for Zn) compared to the values found in French Northern rivers ‘Petite Marque’ and ‘Riez Simon’ near Lille (59) (Ruban et al., 1998) which contain on average 1180 $\mu g\ g^{-1}$ for Zn. This difference might be due to the characteristics of the sediment (TOC for the North of France river = 83 g $kg^{-1}$ whereas average TOC for this study = 37 g $kg^{-1}$). In the case of sediments from canal Gent Terneuzen in Belgium (Cauwenberg et al., 1998), Zn concentrations can

Table 5
Organic micropollutant content ($\mu g\ g^{-1}$) in the sediment collected in 1996, 1999 and 2000

| Code | Y[a] | $HC_{tot}$ | $PAH_{tot}$ | $Ali_{tot}$ | $PCB_{tot}$ | Pesticides | Toluene | Phenols | Code | Y[a] | $HC_{tot}$ | $PAH_{tot}$ | $Ali_{tot}$ | $PCB_{tot}$ | Pesticides | Toluene | Phenols |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| V01 | 1996 | 3 | | | | | | | S3 | 1999 | | 13.0 | 14.6 | | | | |
| V02 | 1996 | 118 | | | | | | | S4 | 1999 | | 11.3 | 33.1 | | | | |
| V03 | 1996 | 522 | 6.66 | | 22.9 | | | <2 | S5 | 1999 | | 5.7 | 33.4 | | | | |
| V04 | 1996 | 45 | 11.78 | | 1.32 | | | <2 | S6 | 1999 | | 83.8 | 55.2 | | | | |
| V05 | 1996 | 213 | | | | | | | S7 | 1999 | | 19.1 | 133.1 | | | | |
| V06 | 1996 | 243 | | | | | | | S8 | 1999 | | 22.6 | 24.3 | | | | |
| V07 | 1996 | 98 | 4.78 | | 1.33 | | | <2 | S9 | 1999 | | 10.3 | 66.1 | | | | |
| V08 | 1996 | 457 | 1.78 | | 0.92 | | | <2 | V1 | 1999 | 388 | | | | | | |
| V09 | 1996 | 65 | | | | | | | V2 | 1999 | 214 | | | | | | |
| V10 | 1996 | 427 | | | | | | | V3 | 1999 | 21 | | | | | | |
| V11 | 1996 | 269 | | | | | | | V4 | 1999 | 121 | | | | | | |
| V12 | 1996 | 66 | | | | | | | V5 | 1999 | 24 | | | | | | |
| V13 | 1996 | 57 | | | | | | | V6 | 1999 | 21 | | | | | | |
| V14 | 1996 | 357 | | | | | | | V7 | 1999 | 63 | | | | | | |
| V15 | 1996 | 71 | | | | | | | V8 | 1999 | 46 | | | | | | |
| V16 | 1996 | 111 | | | | | | | O1 | 1999 | | 1.4 | 12.4 | | | | |
| V17 | 1996 | 56 | | | | | | | O2 | 1999 | | 2.1 | 23.4 | | | | |
| V18 | 1996 | 24 | | | | | | | O3 | 1999 | | 3.5 | 22.7 | | | | |
| V19 | 1996 | 121 | | | | | | | O4 | 1999 | | 3.5 | 44.9 | | | | |
| V20 | 1996 | 117 | | | | | | | O5 | 1999 | | 5.9 | 51.9 | | | | |
| V21 | 1996 | 745 | | | | | | | O6 | 1999 | | 6.2 | 11.1 | | | | |
| V22 | 1996 | 440 | | | | | | <2 | O7 | 1999 | | 5.4 | 38.9 | | | | |
| V23 | 1996 | 60 | 1.4 | | 0.06 | | | | O8 | 1999 | | 10.4 | 60.5 | | | | |
| V24 | 1996 | 263 | | | | | | | O9 | 1999 | | 4.5 | 30.9 | | | | |
| V25 | 1996 | 543 | | | | | | | S10 | 2000 | 459 | 7.5 | <2 | 0.025 | 0.91 | 1 | 1.1 |
| V26 | 1996 | 87 | | | | | | | S11 | 2000 | 44 | 6.2 | <2 | 0.049 | <0.15 | <0.1 | <2 |
| V27 | 1996 | 12 | | | | | | | S12 | 2000 | 918 | 4.8 | <2 | 0.022 | <0.15 | 2.6 | 5 |
| V28 | 1996 | 64 | | | | | | | S13 | 2000 | 90 | 23.7 | 6.9 | 0.012 | <0.15 | <0.1 | <2 |
| V29 | 1996 | 84 | | | | | | | S14 | 2000 | 1135 | 7.7 | 4.4 | 0.094 | <0.15 | 0.9 | <2 |
| V30 | 1996 | 114 | | | | | | | S15 | 2000 | 1252 | 13.1 | 2.9 | 0.129 | <0.15 | 0.4 | <2 |
| V31 | 1996 | 129 | | | | | | | S16 | 2000 | 712 | 7.7 | 4.5 | 0.114 | <0.15 | 1.4 | <2 |
| V32 | 1996 | 6 | | | | | | | O10 | 2000 | 163 | 4.7 | <2 | 0.006 | <0.15 | <0.1 | <2 |
| V33 | 1996 | 12 | | | | | | | O11 | 2000 | 180 | 4.9 | <2 | 0.018 | <0.15 | <0.1 | <2 |
| V34 | 1996 | 1014 | | | | | | | O12 | 2000 | 343 | 3.7 | <2 | <0.005 | <0.15 | 0.3 | <2 |
| V35 | 1996 | 584 | | | | | | | O13 | 2000 | 342 | 12.7 | 5.7 | 0.064 | <0.15 | 0.2 | <2 |
| V36 | 1996 | 225 | | | | | | | O14 | 2000 | 367 | 5.9 | 13 | <0.005 | <0.15 | 0.2 | <2 |
| V37 | 1996 | 266 | | | | | | | O15 | 2000 | 96 | 3.2 | 7.3 | 0.011 | <0.15 | <0.1 | <2 |
| V38 | 1996 | 295 | | | | | | | O16 | 2000 | 380 | 8.5 | 8.1 | <0.005 | <0.15 | 0.5 | <2 |
| S1 | 1999 | | 29.8 | 25.5 | | | | | O17 | 2000 | 194 | 7.9 | 6.7 | <0.005 | <0.15 | 0.6 | <2 |
| S2 | 1999 | | 18.4 | 28 | | | | | | | | | | | | | |

See Fig. 1 for sampling site location.
[a] Year of collection.

even reach 3200 $\mu g\ g^{-1}$ due also to different characteristics (TOC for Belgian canal = 52 g $kg^{-1}$ and fine particles <50 $\mu m$ = 70% whereas average fine particles for this study = 21%). This difference is also observed for other heavy metals such as Cu, Pb, Cd, Ni. Hence, we can assume that sediments from the river Seine basin are less polluted with heavy metals than other rivers or canals situated in industrialised and densely populated areas, this difference being mainly due to the characteristics of the sediment such as the grain size or the organic content which are linked to the heavy metals contents.

To give a general idea of the metal contamination of sediments in the river Seine basin, we compared metal levels to the limits given by the Dutch decree on the quality of DM (circular on target values and intervention values for soil remediation, Ministry of Housing, Spatial Planning and Environment, updated 04/02/2000) which is often used as a reference in Europe. This decree gives two kinds of values: ‘A’ for Alert value which is

Table 6
Organic pollutant content ($\mu g\ g^{-1}$) in the sediment collected before dredging in the Seine basin in 1996, 1999 and 2000

| Site | | $HC_{tot}$ | $PAH_{tot}$ | $Ali_{tot}$ | $PCB_{tot}$ | Pesticides | Toluene | Phenols | Reference |
|---|---|---|---|---|---|---|---|---|---|
| Seine River, 1996–2000 | $n$ | 61 | 38 | 33 | 20 | 15 | 15 | 20 | This study |
| (sediment) | $d_{10}$ | 21 | 3.4 | <2 | <0.005 | 0.91 | 0.2 | 1.5 | |
| | $d_{50}$ | 194 | 6.7 | 13 | 0.03 | 0.91 | 0.5 | 3.0 | |
| | $d_{90}$ | 794 | 20.5 | 54 | 1.3 | 0.91 | 1.5 | 4.6 | |
| | Min | 3 | 1.4 | <2 | <0.005 | 0.91 | 0.2 | 1.1 | |
| | Max | 1252 | 84 | 133 | 22.9 | 0.91 | 2.6 | 5 | |
| | Mean | 302 | 10.9 | 23 | 1.4 | 0.91 | 0.8 | 3.0 | |
| | S.D. | 330 | 13.9 | 27 | 5.2 | – | 0.7 | 2.8 | |
| | CV | 109 | 127 | 118 | 367 | – | 91 | 90 | |
| Seine River, 1995 | Min | | 6 | 61 | 0.5 | | | | Meybeck et al., 1998 |
| (TSS) | Max | | 11 | 100 | 3 | | | | |
| North of France River | Mean | | 770 | | | | | | Ruban et al., 1998 |
| Louisiana waterways, USA | Mean | | 7.3 | | | | | | Mowat and Bundy, 2001 |
| New Jersey, USA | Mean | | 17.4 | | 0.6 | | | | Pollice et al., 1996 |
| Rhine River, Germany | Mean | | 2.6 | | 5.5 | | | | Van Der Hurk et al., 1997 |
| Detroit River, USA | Mean | | 76.8 | | 2.5 | | | | Besser et al., 1996 |

Number of samples ($n$), median ($d_{50}$), first and last decile ($d_{10}$, $d_{90}$), minimum and maximum (min, max), standard deviation (SD), and coefficient of variation in % (CV) of the characteristics given in Table 5.

the target value for sediments; and 'I' for 'Intervention' value for which sediments are considered as contaminated (Table 4). Most samples present metal contents either inferior to the 'A' limit, or between 'A' and an intermediate value [(A+I)/2)] for which sediments show moderate contamination. Fig. 2 shows the distribution of the number of sites showing different quality classes considering the Dutch decree. A few samples present concentrations above this average value (V04, V06, V09 for Hg, V04, V07, S14 for Zn and V03, V07, S10, S12, S14, S15, S16 for Cu), and only two samples show concentrations above the 'I' level: S1 and V02 for Hg. As a result, this comparison with the Dutch decree limits and the comparison with other values found in natural environments tend to indicate that most of the sediment samples from the river Seine basin are lightly to moderately contaminated with heavy metals.

### *3.1.2. Organic micropollutants*

Total PAH levels, i.e. sum of 16 species listed by USEPA, found in the river Seine basin sediments (Table 5 and Table 6) are similar to the values in TSS previously collected in the river Seine (Meybeck et al., 1998). The sediments sampled in the present study contain 6.7 $\mu g\ g^{-1}$ (median) of total PAH with a maximum of 84 $\mu g\ g^{-1}$ and a minimum of 1.4 $\mu g\ g^{-1}$. TSS containing from 6 to 11 $\mu g\ g^{-1}$ (median) of total PAH from upstream Paris to the sampling site at Chatou, downstream Paris, correspond to the site S2 in the present study (Fig. 1). Unlike heavy metals, total PAH contents in sediments and in TSS present similar levels.

Total PAH in the sediments from the river Seine basin show average values of 10.9 $\mu g\ g^{-1}$. In the North of France, a very industrialised region, river sediments contain far higher total PAH contents that can reach 770 $\mu g\ g^{-1}$ (Ruban et al., 1998). Compared to the alert and intervention values from the Dutch decree (04/02/2000), most samples issued from the river Seine basin present concentrations below 'A' value and/or between 'A' and [(A+I)/2] values (Fig. 2). Still, some samples show values superior to [(A+I)/2], i.e. S1, S8, S13 and one sample shows a concentration above the 'I' intervention value, S6. But out of 38 samples, we can assume that the majority of the sediment samples are lightly to moderately contaminated if we consider the Dutch decree, and by comparing the case of the river Seine basin to other urban river basins.

Table 7
Metal and organic micropollutant content ($\mu g\ g^{-1}$) in the leachates of the sediments sampled in 1996, 1999 and 2000

| Code | Y[a] | As | Cd | Cr | Cu | Hg | Ni | Pb | Zn | Al | Fe | Mn | $HC_{tot}$ | $PAH_{tot}$[b] | $Ali_{tot}$[c] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| V03 | 1996 | 0.126 | <0.02 | <0.1 | 2.5 | <0.005 | <0.1 | <0.1 | 6.5 | | | | <1 | 0.016 | |
| V07 | 1996 | | <0.02 | <0.1 | <0.1 | <0.005 | <0.1 | <0.1 | 1.4 | | | | <1 | | |
| V08 | 1996 | | <0.02 | <0.1 | <0.1 | <0.005 | <0.1 | <0.1 | 0.7 | | | | | | |
| V10 | 1996 | 0.09 | <0.02 | <0.1 | 1.6 | <0.005 | <0.1 | <0.1 | 1.3 | | | | | | |
| V32 | 1996 | 0.01 | <0.02 | <0.1 | <0.1 | <0.005 | <0.1 | <0.1 | 0.3 | | | | | | |
| V33 | 1996 | 0.02 | <0.02 | <0.1 | <0.1 | <0.005 | <0.1 | <0.1 | 0.4 | | | | | | |
| V34 | 1996 | 0.35 | <0.02 | <0.1 | <0.1 | 0.06 | <0.1 | <0.1 | 3.9 | | | | | | |
| V35 | 1996 | 0.15 | <0.02 | <0.1 | <0.1 | <0.005 | <0.1 | <0.1 | 1.4 | | | | | | |
| V36 | 1996 | 0.06 | <0.02 | <0.1 | <0.1 | <0.005 | <0.1 | <0.1 | 0.9 | | | | | | |
| V37 | 1996 | 0.02 | <0.02 | <0.1 | <0.1 | 0.14 | <0.1 | <0.1 | <0.1 | | | | | | |
| V38 | 1996 | 0.02 | <0.02 | <0.1 | <0.1 | 0.02 | <0.1 | <0.1 | 0.6 | | | | | | |
| S1 | 1999 | <0.05 | <0.02 | | <0.1 | <0.005 | <0.1 | <0.1 | <0.1 | <1 | 0.1 | 0.1 | | <0.01 | <0.02 |
| S2 | 1999 | <0.05 | <0.02 | | <0.1 | <0.005 | <0.1 | <0.1 | 0.1 | 0.2 | 0.2 | 0.1 | | <0.01 | <0.02 |
| S3 | 1999 | <0.05 | <0.02 | | <0.1 | 0.01 | <0.1 | <0.1 | <0.1 | <1 | <0.1 | <0.1 | | <0.01 | <0.02 |
| S4 | 1999 | <0.05 | <0.02 | | <0.1 | 0.009 | <0.1 | <0.1 | <0.1 | <1 | <0.1 | <0.1 | | <0.01 | <0.02 |
| S5 | 1999 | <0.05 | <0.02 | | <0.1 | 0.009 | <0.1 | <0.1 | <0.1 | <1 | 0.2 | 0.1 | | <0.01 | <0.02 |
| S6 | 1999 | <0.05 | <0.02 | | <0.1 | 0.009 | <0.1 | <0.1 | 0.2 | <1 | 0.4 | <0.1 | | <0.01 | <0.02 |
| S7 | 1999 | <0.05 | <0.02 | | <0.1 | 0.009 | <0.1 | <0.1 | 0.2 | <1 | <0.1 | 0.7 | | <0.01 | <0.02 |
| S8 | 1999 | <0.05 | <0.02 | | <0.1 | 0.009 | <0.1 | <0.1 | <0.1 | <1 | 0.1 | 0.2 | | <0.01 | <0.02 |
| S9 | 1999 | <0.05 | <0.02 | | <0.1 | 0.009 | <0.1 | <0.1 | <0.1 | <1 | <0.1 | 0.2 | | <0.01 | <0.02 |
| V1 | 1999 | <0.05 | <0.02 | <0.1 | <0.1 | <0.005 | <0.1 | <0.1 | <0.1 | | | | <1 | | |
| V2 | 1999 | <0.05 | <0.02 | <0.1 | <0.1 | <0.005 | <0.1 | <0.1 | <0.1 | | | | <1 | | |
| V3 | 1999 | <0.05 | <0.02 | <0.1 | <0.1 | <0.005 | <0.1 | <0.1 | <0.1 | | | | <1 | | |
| V4 | 1999 | <0.05 | <0.02 | <0.1 | <0.1 | <0.005 | <0.1 | <0.1 | <0.1 | | | | <1 | | |
| V5 | 1999 | <0.05 | <0.02 | <0.1 | <0.1 | <0.005 | <0.1 | <0.1 | <0.1 | | | | <1 | | |
| V6 | 1999 | <0.05 | <0.02 | <0.1 | 0.2 | <0.005 | <0.1 | <0.1 | <0.1 | | | | <1 | | |
| V7 | 1999 | <0.05 | <0.02 | <0.1 | 0.1 | <0.005 | <0.1 | <0.1 | 0.2 | | | | <1 | | |
| V8 | 1999 | <0.05 | <0.02 | <0.1 | 0.1 | <0.005 | <0.1 | <0.1 | <0.1 | | | | <1 | | |
| O1 | 1999 | <0.05 | <0.02 | | <0.1 | 0.009 | <0.1 | <0.1 | <0.1 | <1 | <0.1 | 0.3 | | <0.01 | <0.02 |
| O2 | 1999 | <0.05 | <0.02 | | <0.1 | 0.01 | <0.1 | <0.1 | <0.1 | <1 | 0.5 | <0.1 | | <0.01 | <0.02 |
| O3 | 1999 | <0.05 | <0.02 | | <0.1 | 0.009 | <0.1 | <0.1 | <0.1 | <1 | 0.3 | 0.2 | | <0.01 | <0.02 |
| O4 | 1999 | <0.05 | <0.02 | | <0.1 | 0.01 | 0.2 | <0.1 | 0.2 | <1 | 0.1 | 0.2 | | <0.01 | <0.02 |
| O5 | 1999 | <0.05 | <0.02 | | <0.1 | 0.01 | <0.1 | <0.1 | <0.1 | <1 | <0.1 | 0.2 | | <0.01 | <0.02 |
| O6 | 1999 | <0.05 | <0.02 | | <0.1 | <0.005 | <0.1 | <0.1 | <0.1 | 0.3 | 0.3 | <0.1 | | <0.01 | <0.02 |
| O7 | 1999 | <0.05 | <0.02 | | <0.1 | <0.005 | <0.1 | <0.1 | <0.1 | <1 | <0.1 | 0.6 | | <0.01 | <0.02 |
| O8 | 1999 | <0.05 | <0.02 | | <0.1 | <0.005 | <0.1 | <0.1 | <0.1 | <1 | 0.2 | 0.6 | | <0.01 | <0.02 |
| O9 | 1999 | <0.05 | <0.02 | | <0.1 | <0.005 | <0.1 | <0.1 | <0.1 | <1 | <0.1 | 0.3 | | <0.01 | <0.02 |
| S10 | 2000 | <0.05 | <0.02 | <0.1 | <0.1 | <0.005 | 0.1 | <0.1 | 0.2 | <1 | 1.1 | <0.1 | <1 | <0.01 | <0.02 |
| S11 | 2000 | 0.05 | <0.02 | <0.1 | <0.1 | <0.005 | 0.1 | <0.1 | <0.1 | 1.5 | 0.8 | <0.1 | <1 | <0.01 | <0.02 |
| S12 | 2000 | <0.05 | <0.02 | <0.1 | <0.1 | <0.005 | <0.1 | <0.1 | 0.5 | 1.1 | 0.3 | 1.6 | <1 | <0.01 | <0.02 |
| S13 | 2000 | <0.05 | <0.02 | 0.6 | <0.1 | <0.005 | 0.3 | <0.1 | 0.2 | <1 | 2.4 | 0.1 | <1 | <0.01 | <0.02 |
| S14 | 2000 | <0.05 | <0.02 | <0.1 | <0.1 | <0.005 | <0.1 | <0.1 | 0.2 | 1.6 | 0.4 | <0.1 | <1 | <0.01 | <0.02 |
| S15 | 2000 | <0.05 | <0.02 | 0.2 | <0.1 | <0.005 | 0.1 | <0.1 | 0.2 | <1 | 0.7 | <0.1 | <1 | <0.01 | <0.02 |
| S16 | 2000 | <0.05 | <0.02 | <0.1 | <0.1 | <0.005 | <0.1 | <0.1 | 0.3 | 1.6 | 0.4 | 0.1 | <1 | <0.01 | <0.02 |
| O10 | 2000 | <0.05 | <0.02 | 0.3 | <0.1 | <0.005 | 0.2 | <0.1 | 0.2 | <1 | 1.5 | <0.1 | <1 | <0.01 | <0.02 |
| O11 | 2000 | <0.05 | <0.02 | 0.1 | <0.1 | <0.005 | <0.1 | <0.1 | 0.2 | 1.4 | 1.5 | 0.1 | <1 | <0.01 | <0.02 |
| O12 | 2000 | <0.05 | <0.02 | <0.1 | <0.1 | <0.005 | <0.1 | <0.1 | 0.2 | 1.5 | 1.1 | <0.1 | 1.5 | <0.01 | <0.02 |
| O13 | 2000 | <0.05 | <0.02 | 0.2 | <0.1 | <0.005 | 0.1 | <0.1 | 0.2 | <1 | 1.4 | <0.1 | <1 | <0.01 | <0.02 |
| O14 | 2000 | <0.05 | <0.02 | 0.3 | 0.2 | <0.005 | 0.2 | <0.1 | <0.1 | <1 | 1.3 | <0.1 | <1 | <0.01 | <0.02 |

Table 7 *(Continued)*

| Code | Y[a] | As | Cd | Cr | Cu | Hg | Ni | Pb | Zn | Al | Fe | Mn | $HC_{tot}$ | $PAH_{tot}$[b] | $Ali_{tot}$[c] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| O15 | 2000 | <0.05 | <0.02 | <0.1 | <0.1 | <0.005 | <0.1 | <0.1 | 0.2 | 1.7 | 2 | <0.1 | <1 | <0.01 | <0.02 |
| O16 | 2000 | <0.05 | <0.02 | 0.3 | 0.2 | <0.005 | 0.2 | <0.1 | 0.2 | <1 | 1.4 | <0.1 | <1 | <0.01 | <0.02 |
| O17 | 2000 | <0.05 | <0.02 | <0.1 | <0.1 | <0.005 | <0.1 | <0.1 | 0.2 | 1.2 | 1 | <0.1 | <1 | <0.01 | <0.02 |

See Fig. 1 for sampling site location.
[a] Year of collection.
[b] $\mu g\ l^{-1}$.
[c] $mg\ l^{-1}$.

PCBs were also measured in this survey. Total PCB contents obtained in Seine sediment samples collected in 1992 to 1995 (Meybeck et al., 1998) varied from 500 to 3000 ng $g^{-1}$. In the sediments analysed for the present survey, total PCB content varied between detection limit levels (5 ng $g^{-1}$) and 1300 ng $g^{-1}$, with the exceptional site V03 at the Seine–Oise river junction, showing a concentration of 22 900 ng $g^{-1}$. This exceptional value at site V03 may be due to the influence of the Oise river and its associated pollution which joins the Seine river at this site, and also the industries and combined sewer overflows upstream at this site on the Seine river. Thus, we can assume that this range of total PCB concentrations corresponds to the one previously observed on the sediments measured in the river Seine basin (Meybeck et al., 1998). Compared to other river basins, sediments from the river Seine basin show lower total PCB amounts (mean = 1.4 $\mu g\ g^{-1}$) than sediments from the Rhine river in the Netherlands which presents an average level of 5.5 $\mu g\ g^{-1}$ (Van Der Hurk et al., 1997). Again, in that Dutch study, sediments presented loss on ignition of 14% on average, whereas in this study, the mean organic matter content is of only 8%. This difference might explain the PCB contents since PCB contents vary as a function of organic matter contents (Fowler, 1990). Compared to the Dutch decree, most samples from the river Seine basin showed total PCB concentrations below the ‘A’ value and between ‘A’ and [(A+I)/2] intermediate value (Fig. 2). Nevertheless, the concentration of sample V08 on Oise river was above [(A+I)/2] and concentrations of samples V03, V04 and V07 on Seine river downstream Paris were above ‘I’ value. Again, concerning the total PCB level, as for heavy metals and PAH, we can state that most of the sediment samples from the river Seine basin are lightly to moderately contaminated compared to Dutch criteria.

We also measured pesticide, toluene and phenols contents in the sediments: we do not discuss these results in the present paper since most values were found below detection limits (Table 5 and Table 6).

### 3.1.3. Leachates and pore water quality

Concentrations of micropollutants in the leachates obtained from the river Seine basin sediments are mostly below detection limits (Table 7): exceptions are rare. We also measured micropollutants in porewaters. Concentrations were also frequently below detection limits (Table 8). From these results, we can assume that there is only a minor short term risk of micropollutants release by DM. Alternatively, we suggest that the leaching test performed by mixing a 100 g/l suspension of sediment, during 24 h, is unable to simulate sediment diagenesis under anoxic conditions. Thus, it is difficult to anticipate the behaviour of micropollutants once the sediment has been dredged, unless we monitor the evolution of dredged materials with time in situ (Carpentier, 2002).

## 3.2. Geographic distribution and correlation analysis

Correlation analysis was performed to assess the probable link between micropollutants and physico-chemical parameters presented and discussed in a previous paper (Carpentier et al., 2002), as well as between micropollutants themselves (Table 9). The correlation between the sediments organic matter content and some heavy metals is significant ($r > 0.7$, $n > 46$, $P < 0.01$): Cr; Ni; As; Fe; Al;

Table 8
Metal and organic micropollutant content ($\mu g\ l^{-1}$) in porewaters of sediments sampled in 1996, 1999 and 2000

| Code | Y[a] | As | Cd | Cr | Cu | Hg | Ni | Pb | Zn | Al | Fe | Mn | $HC_{tot}$ | $PAH_{tot}$ | $Ali_{tot}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| S1 | 1999 | <5 | <2 | | 10 | <0.5 | <10 | <10 | 40 | <10 | 168 | 1910 | | 0.18 | <20 |
| S2 | 1999 | 8.5 | <2 | | <10 | <0.5 | <10 | <10 | 40 | 20 | 310 | 6970 | | 0.2 | 40 |
| S3 | 1999 | 8.6 | <2 | | <10 | 0.73 | <10 | <10 | 30 | <10 | 186 | 2350 | | <0.01 | <20 |
| S4 | 1999 | <5 | <2 | | <10 | 0.79 | <10 | <10 | 20 | <10 | 215 | 5350 | | <0.01 | <20 |
| S5 | 1999 | <5 | <2 | | <10 | 0.69 | <10 | <10 | 20 | <10 | 299 | 5670 | | <0.01 | 20 |
| S6 | 1999 | <5 | <2 | | <10 | 0.74 | <10 | <10 | 30 | <10 | 300 | 560 | | 0.35 | <20 |
| S7 | 1999 | 10.8 | <2 | | <10 | 1.06 | <10 | <10 | 10 | 10 | 1010 | 552 | | 0.22 | 40 |
| S8 | 1999 | <5 | <2 | | <10 | 0.5 | <10 | <10 | 50 | <10 | 665 | 2950 | | 0.27 | <20 |
| S9 | 1999 | 5.6 | <2 | | <10 | 0.83 | <10 | <10 | <10 | <10 | 282 | 5620 | | <0.01 | <20 |
| V1 | 1999 | 9.4 | <2 | <10 | <10 | <0.5 | 26 | <10 | 20 | | | | <50 | | |
| V2 | 1999 | 5.8 | <2 | <10 | <10 | <0.5 | 25 | <10 | 20 | | | | <50 | | |
| V3 | 1999 | <5 | <2 | <10 | <10 | 0.73 | <10 | <10 | 10 | | | | *x* | | |
| V4 | 1999 | 6.6 | <2 | <10 | 20 | <0.5 | <10 | <10 | 30 | | | | <50 | | |
| V5 | 1999 | <5 | <2 | <10 | <10 | <0.5 | 14 | <10 | 20 | | | | <50 | | |
| V6 | 1999 | <5 | <2 | <10 | <10 | <0.5 | 17 | <10 | 20 | | | | <50 | | |
| V7 | 1999 | <5 | <2 | <10 | <10 | <0.5 | 13 | <10 | 20 | | | | <50 | | |
| V8 | 1999 | <5 | <2 | <10 | <10 | <0.5 | 26 | <10 | 20 | | | | 190 | | |
| O1 | 1999 | 15.1 | <2 | | <10 | 0.76 | 11 | <10 | 40 | <10 | 309 | 1230 | | <0.01 | <20 |
| O2 | 1999 | 11.8 | <2 | | <10 | 0.7 | <10 | <10 | 30 | <10 | 524 | 477 | | <0.01 | <20 |
| O3 | 1999 | <5 | <2 | | <10 | 0.66 | <10 | <10 | <10 | <10 | 170 | 521 | | <0.01 | <20 |
| O4 | 1999 | <5 | <2 | | <10 | 0.65 | 211 | <10 | 40 | <10 | 634 | 610 | | <0.01 | <20 |
| O5 | 1999 | <5 | <2 | | <10 | 0.76 | <10 | <10 | 20 | <10 | 309 | 935 | | <0.01 | <20 |
| O6 | 1999 | <5 | <2 | | <10 | <0.5 | <10 | <10 | 40 | <10 | 191 | 423 | | <0.01 | <20 |
| O7 | 1999 | <5 | <2 | | <10 | <0.5 | <10 | <10 | 40 | 20 | 1600 | 358 | | 0.1 | <20 |
| O8 | 1999 | <5 | <2 | | <10 | <0.5 | <10 | <10 | 30 | 10 | 1500 | 283 | | 0.1 | <20 |
| O9 | 1999 | <5 | <2 | | <10 | <0.5 | <10 | <10 | 30 | <10 | 204 | 214 | | <0.01 | <20 |
| S10 | 2000 | | | | | | | | | | | | <50 | | |
| S11 | 2000 | | | | | | | | | | | | | | |
| S12 | 2000 | | | | | | | | | | | | 80 | | |
| S13 | 2000 | | | | | | | | | | | | | | |
| S14 | 2000 | | | | | | | | | | | | 120 | | |
| S15 | 2000 | | | | | | | | | | | | <50 | | |
| S16 | 2000 | | | | | | | | | | | | 60 | | |
| O10 | 2000 | | | | | | | | | | | | <50 | | |
| O11 | 2000 | | | | | | | | | | | | <50 | | |
| O12 | 2000 | | | | | | | | | | | | <50 | | |
| O13 | 2000 | | | | | | | | | | | | <50 | | |
| O14 | 2000 | | | | | | | | | | | | <50 | | |
| O15 | 2000 | | | | | | | | | | | | <50 | | |
| O16 | 2000 | | | | | | | | | | | | <50 | | |
| O17 | 2000 | | | | | | | | | | | | <50 | | |

See Fig. 1 for sampling site location.
[a] Year of collection.

and Mn; as well as the correlation between organic matter and total hydrocarbons ($r=0.63$, $n=61$, $P<0.01$). This kind of correlation has often been demonstrated in literature (Irwin et al., 1997). Also, as expected, fine particles percentage was correlated significantly to some heavy metal contents: Cr; As; Fe; Al; and Mn ($r>0.7$, $n>46$, $P<0.01$); and to Ni ($r=0.47$, $n=71$, $P<0.01$). Fine particles were also significantly correlated to total hydrocarbons ($r=0.36$, $n=61$, $P<0.01$). Concerning organic micropollutants and heavy metals, we found out that total hydrocarbon concentrations

Table 9
Correlation matrix of analysed parameters for sediment samples of the Seine basin from 1996, 1999 and 2000

| | TOC | Density | Humidity | OM | Fine particles | $HC_{tot}$ | $PAH_{tot}$ | $Ali_{tot}$ | $PCB_{tot}$ | Toluene | As | Cd | Cr | Cu | Hg | Ni | Pb | Zn | Al | Fe | Mn |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| TOC | 1 | | | | | | | | | | | | | | | | | | | | |
| Density | **−0.70** | 1 | | | | | | | | | | | | | | | | | | | |
| Humidity | 0.44 | **−0.86** | 1 | | | | | | | | | | | | | | | | | | |
| OM | 0.36 | −0.77 | **0.69** | 1 | | | | | | | | | | | | | | | | | |
| Fine particles | −0.03 | **−0.56** | **0.53** | **0.51** | 1 | | | | | | | | | | | | | | | | |
| $HC_{tot}$ | **0.58** | **−0.60** | **0.68** | **0.63** | 0.36 | 1 | | | | | | | | | | | | | | | |
| $PAH_{tot}$ | 0.16 | 0.11 | −0.10 | −0.17 | −0.27 | 0.07 | 1 | | | | | | | | | | | | | | |
| $Ali_{tot}$ | 0.20 | 0.29 | 0.26 | −0.32 | −0.38 | −0.19 | 0.29 | 1 | | | | | | | | | | | | | |
| $PCB_{tot}$ | 0.34 | −0.17 | 0.22 | −0.35 | −0.11 | 0.07 | −0.04 | −0.24 | 1 | | | | | | | | | | | | |
| Toluene | 0.54 | −0.43 | 0.59 | 0.59 | 0.38 | 0.58 | −0.18 | −0.26 | 0.21 | 1 | | | | | | | | | | | |
| As | 0.22 | **−0.68** | 0.40 | **0.81** | **0.71** | **0.70** | −0.17 | **−0.52** | −0.14 | 0.60 | 1 | | | | | | | | | | |
| Cd | **0.59** | −0.13 | 0.17 | 0.20 | 0.00 | 0.20 | 0.24 | 0.39 | −0.05 | 0.54 | 0.05 | 1 | | | | | | | | | |
| Cr | **0.47** | **−0.66** | **0.77** | **0.73** | **0.66** | **0.60** | −0.05 | −0.03 | 0.11 | 0.45 | **0.64** | 0.37 | 1 | | | | | | | | |
| Cu | **0.62** | **−0.51** | **0.51** | **0.47** | 0.28 | **0.62** | 0.13 | −0.02 | 0.50 | **0.75** | 0.39 | **0.47** | **0.71** | 1 | | | | | | | |
| Hg | 0.27 | 0.18 | −0.02 | −0.07 | −0.17 | −0.07 | 0.23 | 0.04 | 0.19 | **0.67** | −0.13 | 0.27 | −0.06 | 0.23 | 1 | | | | | | |
| Ni | **0.48** | −0.62 | **0.77** | **0.77** | **0.47** | **0.61** | −0.13 | 0.00 | 0.11 | 0.58 | **0.60** | 0.38 | **0.91** | **0.51** | 0.07 | 1 | | | | | |
| Pb | 0.32 | −0.20 | 0.21 | 0.14 | −0.12 | 0.34 | 0.16 | 0.19 | 0.47 | **0.75** | 0.01 | **0.48** | 0.25 | **0.61** | 0.30 | 0.17 | 1 | | | | |
| Zn | **0.50** | −0.58 | **0.59** | **0.54** | 0.30 | **0.63** | 0.08 | 0.05 | 0.49 | **0.65** | 0.40 | **0.56** | **0.78** | **0.89** | 0.18 | **0.63** | **0.75** | 1 | | | |
| Al | 0.26 | −0.62 | 0.37 | **0.82** | **0.76** | **0.78** | −0.24 | **−0.47** | 0.45 | 0.48 | **0.94** | −0.01 | **0.86** | **0.51** | −0.16 | **0.62** | 0.02 | **0.52** | 1 | | |
| Fe | 0.12 | −0.40 | 0.37 | **0.75** | **0.80** | **0.57** | −0.35 | **−0.49** | 0.24 | 0.36 | **0.91** | −0.06 | **0.83** | 0.34 | −0.13 | **0.63** | −0.16 | 0.37 | **0.89** | 1 | |
| Mn | 0.13 | −0.44 | 0.07 | **0.83** | **0.68** | **0.74** | −0.21 | **−0.59** | 0.39 | 0.60 | **0.92** | −0.05 | **0.86** | 0.43 | −0.14 | 0.40 | −0.05 | 0.43 | **0.84** | **0.83** | 1 |

$n > 15$. The highly significant $(P < 0.01)$ correlations are indicated in bold.

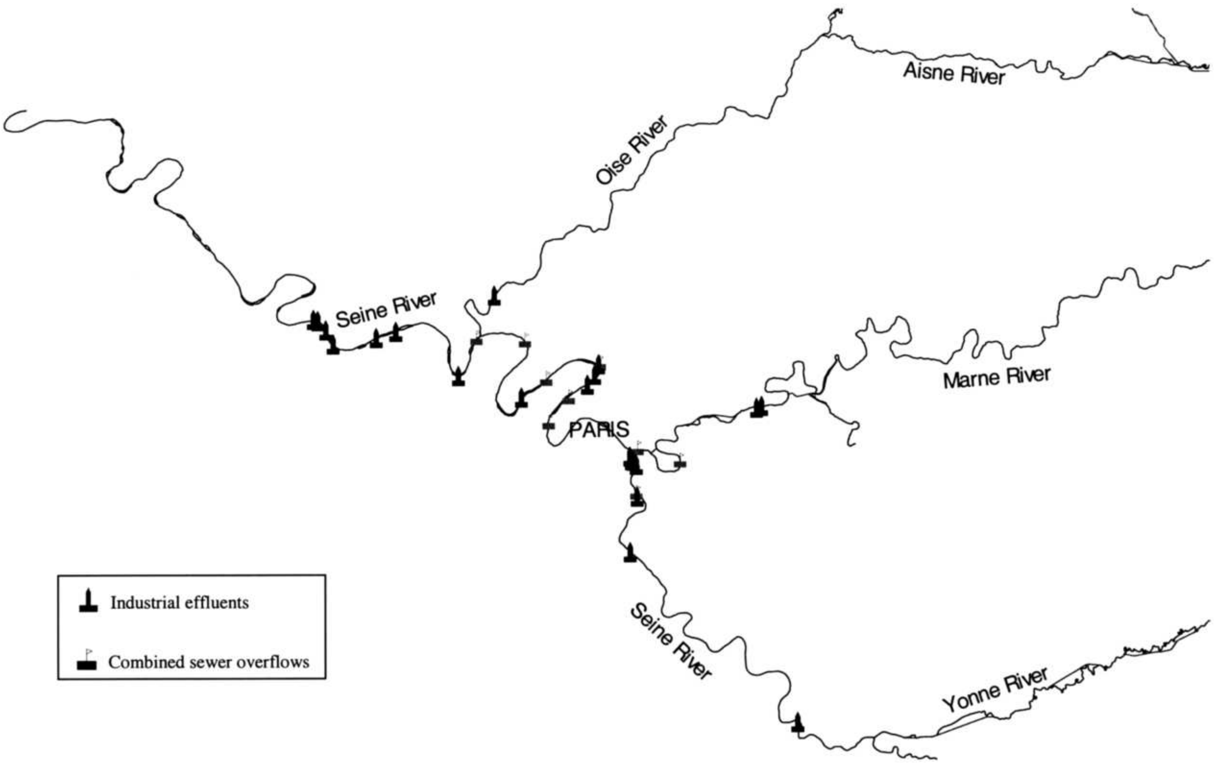


Fig. 3. Sites of major industrial effluents inventoried for this study and combined sewer overflows (listed in Meybeck et al., 1998) in the river Seine basin.

were significantly correlated ($r > 0.7$, $n > 33$, $P < 0.01$) to some heavy metal concentrations: Cr; Zn; Ni; Cu; As; Al; and Mn, probably indicating the influence of industrial or urban runoff. But total PAH and total PCB levels were not correlated to one another or with heavy metals. A few heavy metals were correlated to one another: Cr with Zn; Ni; Cu; Fe; Al; Mn. The fact that Cr is correlated to Fe, Al and Mn, which are crustal metals, corresponds to the fact that part of Cr in the environment is natural. Its correlation with Zn, Ni and Cu could be related to the anthropogenic origin of Cr, since Ni, Cu and Zn are involved in many industrial processes (Rodier et al., 1996). Fe, Al and Mn are strongly correlated ($0.83 < r < 0.89$) because they are crustal metals and, therefore, belong to the matrix of the sediments (Rodier et al., 1996), but their content is also strongly linked to the As one ($0.91 < r < 0.94$), which is quite unexpected. These results suggest As is both adsorbed onto organic matter and charged surfaces of clays (Irwin et al., 1997).

We performed a geographic distribution analysis using Mapinfo® Geographic Information System in order to present a general overview of the micropollutant content of sediments along the whole river Seine basin, and to try and link the most polluted areas to the main point sources identified in the same region (combined sewer overflows were listed in Meybeck et al., 1998 and industrial effluents were inventoried for this study) (Fig. 3). Unlike physico-chemical parameters, micropollutants show a very clear pattern: highly contaminated sites are regularly situated in the same areas of the river Seine basin, whatever the micropollutant considered. Downstream all major source of pollutants, i.e. industrial effluent and/or combined sewer overflow sites, the sediment samples present higher micropollutant contents. Fig. 4 illustrates this relation with Zn: the eight ‘hot

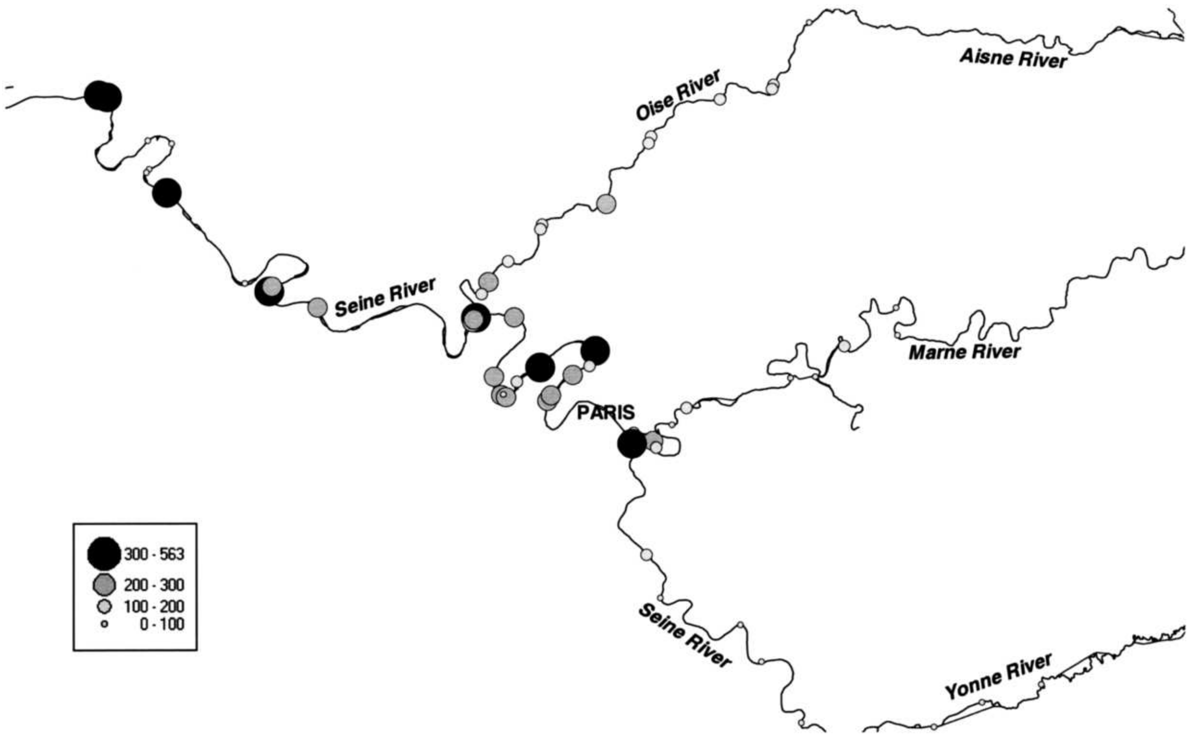


Fig. 4. Geographic distribution of Zn content ($\mu g\ g^{-1}$) in the sediment collected along the river Seine basin during 1996, 1999 and 2000 campaigns: highly contaminated sites correspond to the 'hot spots' (Fig. 1) and to the sites of possible pollution release (Fig. 3).

spots' correspond exactly to a cluster of industries and waste water treatment plants as well as combined sewer overflow sites. We can state that these contamination distribution maps represent a recent fingerprint of diverse pollution, since the specific areas sampled for this study are dredged frequently and, thus, the surface sediment that has been sampled was present and contaminated for less than 3 years. It is important to note that similar distribution maps were also found for Cu, Pb, Cr, As, Hg, Ni, Cd and total hydrocarbons, and to a lesser extent, for total PAH and PCB and Fe, Al and Mn.

## 4. Conclusions

Before dredging operations within the river Seine basin, the quality of the sediments to be dredged is regularly checked (once every 3 years) in order to determine the management strategy of dredged materials. In this survey, we present the results obtained for samples collected in 1996, 1999 and 2000 and suggest dredging and management strategies. Depending upon the sediment contamination, the following strategies are recommended: (1) dumping of light or moderately polluted sediments in quarries referring to the limits given by the Dutch decree on target values and intervention values for soil remediation, Ministry of Housing, Spatial Planning and Environment, updated 04/02/2000; (2) identifying some 'hot spot' sites and give the sediments dredged here a separate cleaning (sieving, hydrocycloning) in order to discriminate highly contaminated fine particles from sand or gravel which can be reused.

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